OBSERVATIONAL MAGNETOMETER CALIBRATION WITH THE HUBBLE SPACE TELESCOPE'S NEW MAGNETOMETERS

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ABSTRACT

The two magnetometers recently replaced on the Hubble Space Telescope during the STS-61 Servicing Mission are now being used successfully for Coarse Attitude Determination during spacecraft vehicle safemode recovery operation. The magnetometer alignments relative to the spacecraft's vehicle's reference frame and the magnetic coupling of the sensors to the four magnetic torquer bars were determined. Coarse Attitude determination errors are now reduced to an average of 0.6 degrees.

Magnetometer Sensing System calibration and Coarse Attitude determination testing with the new calibration parameters is a geometrical problem. Telemetered earth magnetic field data was collected at twenty-six different vehicle attitudes. The spacecraft attitudes selected were distributed as widely apart as possible throughout the Geocentric Inertial Coordinate reference frame. It is also desirable to sample the Earth's magnetic field over as many different locations of the spacecraft's passage over the Earth as possible, within the limitation of the +/- 28.5 degree orbital inclination. A full range of magnetic moment outputs from the torquer bars needs to be sampled, +/- 3600 amp-meters squared, as well as data when the torquer bars have zero current. Graphic utilities were also developed to visually aid in optimizing the data collection process. Finally, a brief discussion of a method for collecting data for future calibrations is suggested.

1.0 INTRODUCTION

The Magnetic Sensing System (MSS) consists of the two magnetometers onboard the Hubble Space Telescope (HST). The changing Earth magnetic field vectors telemetered from the HST magnetometers during an HST orbit are used by the Payload Applications Support Software Operations (PASSOPS) Group to compute coarse attitudes. The attitude determination software uses the QUEST algorithm, which is described in Reference 1. In order to successfully calibrate the scale factor alignment matrices and biases of each magnetometer relative to the HST vehicle axes, it is necessary to account for the magnetic field from the four magnetic torquer bars onboard HST, which are used in vehicle momentum management. To perform accurate Coarse Attitude determinations the magnetometers need to be calibrated.

The intent of this paper is to focus on the MSS data collection aspects, the computation of the calibration parameters for the HST magnetometers and torquers, and the verification of the

MSS calibration results with computed coarse attitudes. Based on this experience a new method for acquiring data for the full MSS calibration is suggested.

2.0 CALIBRATION ALGORITHM

The MSS calibration algorithm is described below. The calibration will provide estimates of the misalignments for both magnetometers with respect to the HST vehicle axes, magnetometer biases, and the coupling matrix to the magnetic torquers. The software to perform the MSS calibration was developed by Computer Sciences Corporation as part of the HST PASS system. The inputs to the MSS calibration program include HST ephemeris data, a geomagnetic field model, MSS sensed magnetic field, fine attitude solutions, telemetered magnetic dipole moments from the four torquers bars, and database MSS calibration parameters. Nominally, the duration of the each record is set to be one minute to ensure that at least one telemetry update from each magnetometer and torquer rod is included in the prepared data record.

A standard Least Squares method is used to obtain the calibration parameters. The loss function is minimized with respect to the residual bias parameters. The residual bias parameters that are determined from minimizing the Loss Function are [S], [T], and b, which are defined below. The form of the matrix [T] is based on the far field approximation of a single dipole centered in the HST vehicle reference frame.

LOSS = SUM(i=1 to N) a(i)*|H(i) - b - [S]*B(i) - [T]*D(i)|**2
FUNCTION

where

N = number of valid MSS observations

a(i) = normalized weight for the ith observation
= 1/(|H(i)|**2 + a'**2)*Sum(j=1 to N)(|H(j)|**2 + a'**2)

H(i) = geomagnetic field measurement error
= B(i) - [A]*B0(i)

[A] = Fine Attitude (Computed by FINATT PASS application)

B0(i) = geomagnetic field (gauss) in Geocentric Inertial Coordinates (GCI)

B(i) = magnetic field as measured by the MSS in the HST vehicle reference frame and converted for Magnetic Torquer Electronics (MTE) bias and offset bias (gauss)

a' = user-specified weight

b = offset bias (gauss)

[S] = misalignment bias matrix

[T] = bias in magnetic torquer coupling matrix (gauss per ampere-meter squared)

D(i) = 3-by-1 magnetic moment vector in the HST vehicle reference frame (ampere-meters squared)

3.0 ORBITAL VERIFICATION CALIBRATION

Shortly after HST was launched in April 1990, magnetometer bias offsets were computed for each magnetometer. One orbit's worth of data, 96 minutes, is sufficient for the bias determination. The Coarse Attitude Determination Software includes the option for computing each magnetometer offset bias according to the attitude independent algorithm described in Ref. 2. The MSS calibration software (MSSCAL) also computes each magnetometer's offset bias together with each magnetometer's scale factor and alignment matrix. The magnetometer offset bias computation cannot be done separately from the magnetometer scale factor alignment matrice determination when MSSCAL is run. On option the MSSCAL software user may update each MTE coupling matrix.

In order to achieve an accurate alignment determination, magnetic field data needs to be gathered at HST pointing attitudes distributed as much as possible over the celestial sphere to achieve a good distribution of magnetic field components along each vehicle axis. Typically 25 spacecraft attitude pointings spread over the 4 pi steradians are used. Special attention is also needed to sample the full torquer range of +/- 3600 amp-meters**2. These special data requirements are met in time as HST maneuvers around the celestial sphere while conducting normal science operations. MSSCAL was not used successfully during orbital verification (OV) because of a lack of sufficiently well distributed data. During OV spacecraft pointings were generally confined to the vehicle safemode attitudes, - V1, or + V3 sunpoint, or to star clusters selected for calibration of the three Fine Guidance Sensors.It took a year before the first successful full magnetometer calibration was completed.

Table 1 lists examples of the accuracies for Coarse Attitude determinations with the two HST magnetometers after calibration of the offset biases with the attitude independent algorithm from Reference 2, but before the full calibration was performed. Approximately twenty minutes of MSS data is used for each Coarse Attitude determination. These intervals were specifically selected in order in include the higher range of magnetic moment outputs from the torquer bars experienced during HST vehicle momentum management, (+/- 3600 amp-meters**2).

Each Coarse Attitude error listed in Table 1 refers to the Root Sum Square (RSS) of the HST vehicle axis errors. A Fine Attitude, which is accurate to better than 7 arcseconds, was computed, using a combination of HST Fixed Head Star Trackers' (FHST) observations, and/or Fine Guidance Sensors, to be used as reference against which the Coarse Attitude accuracy was measured. The RSS attitude error is derived from the fourth component of the quaternion which represents the angle between the Coarse and Fine Attitude quaternions. These attitude errors were well above the required accuracy of 5 degrees (2 sigma), especially during periods of high torquer bar output.

Figure 1 shows the magnetic moment output from the 4 HST torquer rods over approximately one HST orbit at a pointing attitude of Right Ascension (RA), 83.7 degrees, Declination (DEC), 72.1 degrees, and Roll, 272 degrees. Up to two HST orbits, approximately three hours of magnetic moments from each torquer bar can be retained on the run time graphic display. By using this tool one is able to select an optimal time period with the maximum range of magnetic moments for a given HST attitude pointing when doing the full MSS calibration data preparation with the PASSOPS FINATT software.

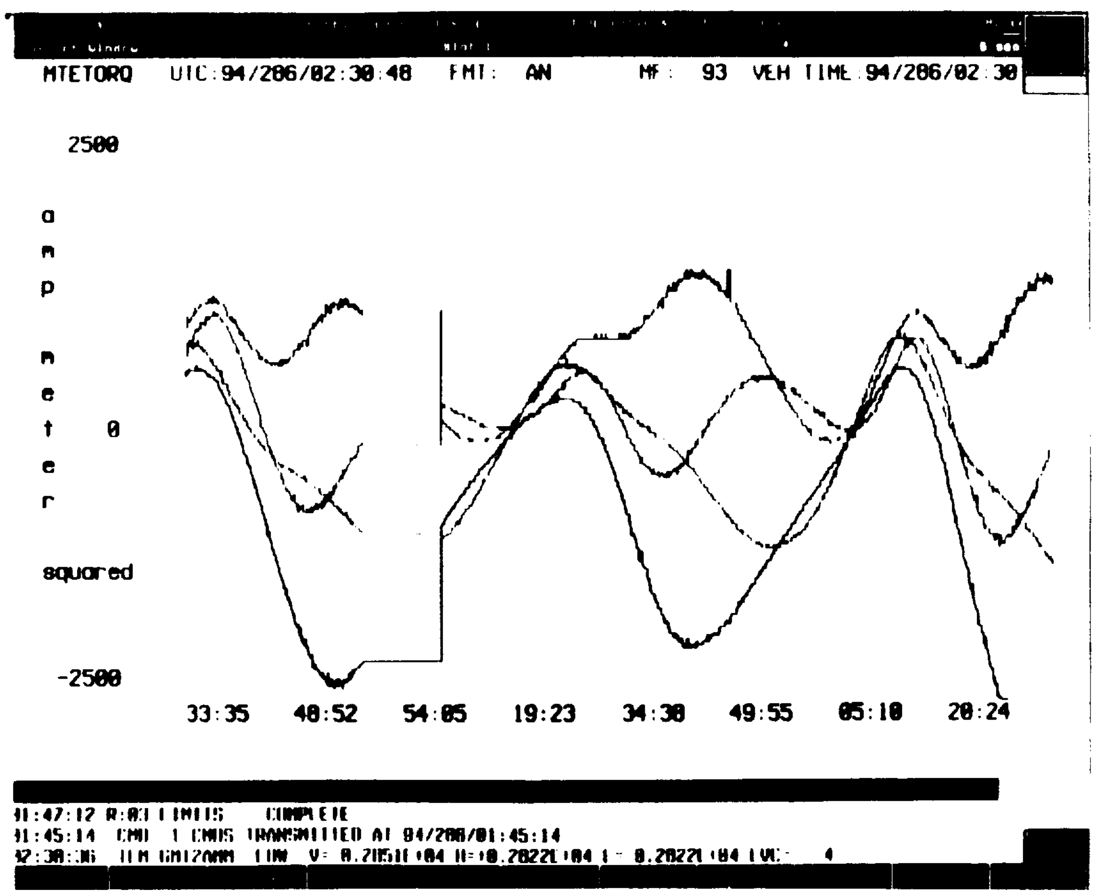


Figure 1: Magnetic Torques From the 4 HST Torquer Rods

Table 1: HST COARSE ATTITUDE ACCURACY USING TWO MAGNETOMETER SENSORS DURING PERIODS OF HIGH MAGNETIC TORQUER CURRENTS
(Calibrated Biases, Uncalibrated Scale/Alignment, and Torquer Coupling)

	Time Period (Year.Day of Year/Universal Time)	Coarse Attitude Error (RSS) (Degrees)
1)	1991.009/03:51-04:09	4.0
2)	1991.010/03:54-04:12	5.0
3)	1991.011/04:02-04:15	7.4
4)	1991.016/05:24-05:42	9.9
5)	1991.021/03:06-03:31	8.9
6)	1991.025/00:55-01:12	18.0
7)	1991.136/00:01-00:18	16.3
8)	1991.197/13:45-14:03	26.3
9)	1991.206/05:16-05:33	7.3
10)	1991.208/04:01-04:24	8.2

4.0 POST ORBITAL VERIFICATION CALIBRATION

The first Full MSS calibration was completed by July 1991 - Reference 3. With the MSS parameters derived in July 1991 for initialization, the full calibration was redone and completed by April 1992 - Reference 4. Coarse Attitude determinations using the updated April 1992 MSS calibration had errors less than the five degree two sigma requirement. A slight improvement in Coarse Attitude determination was noted (Reference 5) in June 1992 when the MSS calibration with the April 1992 data set was redone with weight specified as the standard deviation of the residuals from the calibration Loss function.

5.0 FIRST SERVICING MISSION CALIBRATION

After the First HST Servicing Mission (FSM), the MSS calibration had to be redone because the HST magnetometers were replaced. The process was completed in three months without impacting HST science operations or other vehicle checkout activities by using serendipitous data collection. The December 1993 calibration data span lasted three weeks; and the verification data span was completed after one month. The verification data span lasted slightly longer than the calibration data span in order to avoid using any of the HST pointing attitudes used in the calibration.

Figure 2 shows the HST vehicle attitude pointings selected for acquiring MSS calibration data, and the pointings used to compute Coarse Attitudes to verify the new calibration parameters. The large data gap in Figure 2 coincides with the solar constraint zone during the December 1993 MSS calibration data collection.

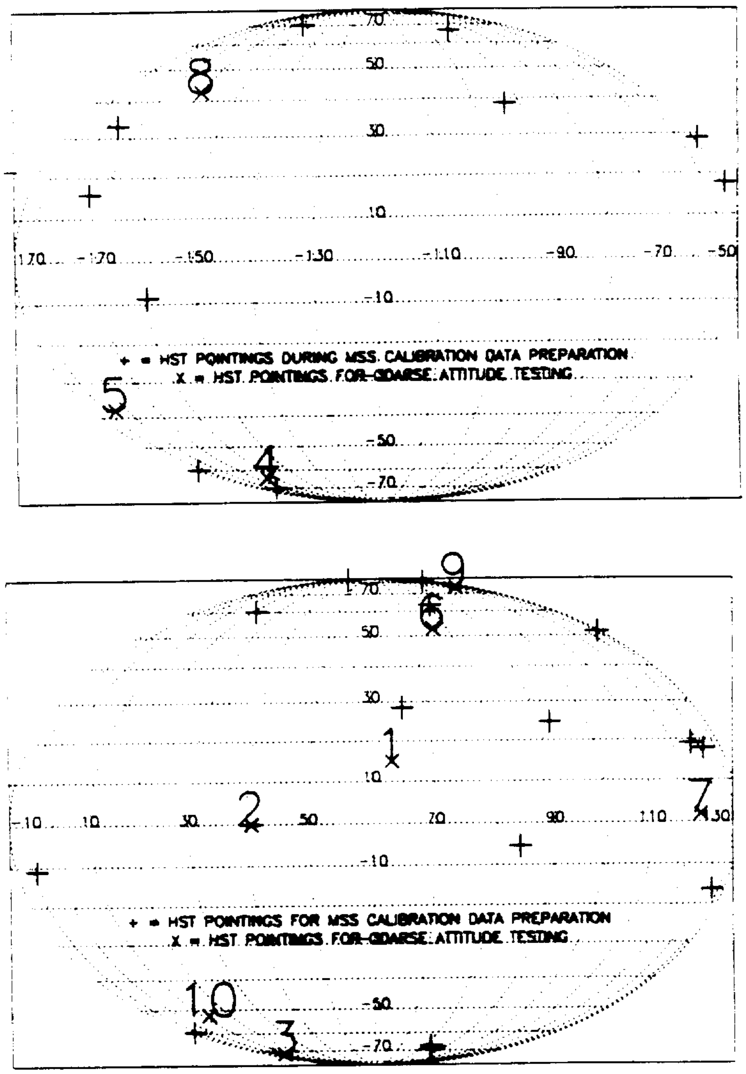


Figure 2: HST Pointings for MSS Calibration
(December 1993 MSS Calibration)

Typically at least 10 HST vehicle attitude pointings are selected to verify the new MSS calibration parameters record.

Table 2 lists the Fine Attitude pointings illustrated in Figure 2. The time noted is the midpoint of a five minute interval. The magnetic moment range occurs during the twenty minute time period that Coarse Attitude determination was performed to verify the calibration. Spacecraft passage through the South Atlantic Anomaly (SAA) is noted if it occurred during the twenty minute interval. The relevance of HST passage through the SAA will be examined latter in this section.

Table 3 lists the angular deviation between the Coarse and Fine Attitude quaternion for each of the test case attitudes numbered in Figure 2. Coarse Sun Sensor (CSS) observations were sometimes included as part of the study to test the effect on the

Coarse Attitude determination. The best result for Coarse Attitude determination test cases using the new MSS calibration record shows an average angular deviation of 0.6 degrees, with a standard deviation on 0.4 degrees. This result is highlighted at the bottom of Table 3. A Column Header Explanation for Table 3 is appended.

Figure 3 graphically represents the results in Table 3.

Table 2: HST Pointings Used to Test the December 1993 MSS Calibration of Scale, Alignment, Bias and Torquer Coupling

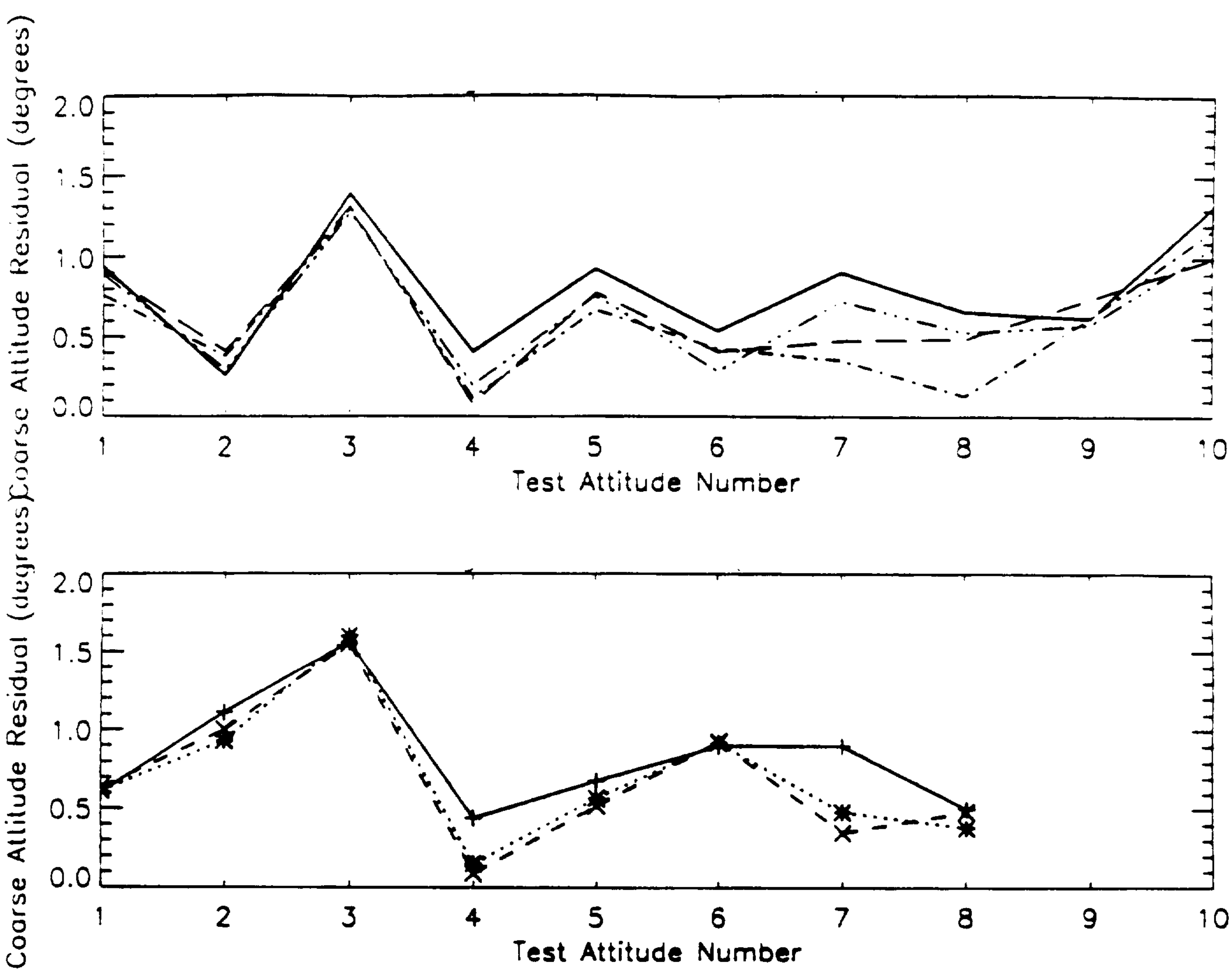
Test Attitude Number	Universal Time	Fine Attitude (RA,DEC,ROLL) (Degrees)			Magnetic Moment Range (Amp-meters**2)	SAA?
1) 94.002	08:27:30	63.2178	14.9311	110.0644	-116 to 1597	Yes
2) 94.010	02:52:32	40.7245	- 0.0749	105.6122	-2234 to 2064	Yes
3) 94.011	04:40:30	6.1297	-72.1848	81.3741	-2130 to 1538	Yes
4) 94.013	11:09:30	195.9780	-63.7722	252.4438	-831 to 1864	No
5) 94.016	16:42:30	174.7786	-37.8259	232.4462	-1221 to 3241	No
6) 94.028	05:44:30	76.1742	52.7765	71.9177	-1261 to 2411	No
7) 94.033	14:07:30	123.8483	1.9098	141.8252	-1854 to 1195	No
8) 94.036	12:55:30	200.3389	42.5863	293.4895	-2949 to 1366	No
9) 94.013	16:11:30	122.7403	74.9519	14.9680	-747 to 1036	No
10) 94.014	03:22:30	12.5868	-52.2190	93.6173	-2320 to 889	Yes

Table 3: RSS Coarse Attitude Residuals (Degrees) From Fine Attitudes At Test Attitudes (1-10) using the FSM MSS Calibration

	Nominal (CSS)	Nominal	New MSS (CSS)	New MSS [(WT=.003	New MSS (CSS))]	New MSS (Align) (+ Bias)	New MSS (Align+Bias) (Wt1=.003) (Wt2=.004)
1)	0.60	0.94	0.61	0.76	0.63	0.89	0.91
2)	1.11	0.26	0.93	0.38	1.00	0.30	0.41
3)	1.56	1.40	1.60	1.30	1.55	1.28	1.32
4)	0.44	0.41	0.15	0.12	0.09	0.20	0.08
5)	0.68	0.93	0.57	0.67	0.52	0.76	0.78
6)	0.90	0.54	0.92	0.43	0.93	0.29	0.41
7)	0.90	0.91	0.48	0.36	0.35	0.73	0.48
8)	0.50	0.66	0.38	0.13	0.48	0.53	0.49
9)		0.62		0.62		0.58	0.74
10)		1.32		1.18		1.07	1.00
Mean RSS Angular Deviation and Standard Deviation by Column							
Mean RSS	0.84	0.79	0.70	**0.60**	0.69	0.66	0.66
RMS	0.37	0.37	0.45	**0.40**	0.45	0.35	0.36

Table 3 Column Header Explanations

a) Nominal (CSS)	-	The currently operational (pre FSM) MSS magnetometer alignment, Bias, and Magnetic Torquer scaling/alignment matrice are used to compute the Coarse Attitude pointings of HST. HST Coarse Sun Sensor observations are included.
b) Nominal	-	Same as Nominal (CSS), but no CSS observations
c) New MSS (CSS)	-	The December 1993 MSS calibration parameters are used to compute Coarse Attitudes.
d) New MSS (CSS) (WT= 0.003)	-	A user specified data weighting factor, a', from Section 2.1, was used when calibrating both MSS 1 and 2.
e) New MSS (WT= 0.003)	-	Same as d), except no CSS observations are include in Coarse Attitude determination
f) MSS (Align + Bias)	-	A new MSS alignment and bias determination was computed with post FSM data. The magnetic torquer coupling is not recalibrated.
h) MSS (Align + Bias) (WT1 = 0.003) (WT2 = 0.004)		Same as MSS (Align + Bias), except MSS 1 and 2 had different values for a' when the calibration was performed for each sensor.



TYPE OF MSS CALIBRATION USED TO COMPUTE COARSE ATTITUDE	SYMBOL/LINESTYLE
PLOT I	
b) NOMINAL	Solid -
f) NEW MSS (WT= .003)	Dash dot - .
g) MSS (ALIGN + BIAS)	Dash dot dot - . .
h) MSS (ALIGN + BIAS) (WT1=.003, WT2=.004)	Long dashes __ __ __
PLOT II	
a) NOMINAL (CSS)	+
c) NEW MSS (CSS)	*
e) NEW MSS (CSS, WT= .003)	X

Figure 3: Coarse Attitude Angular Deviation (RSS) vs. Attitude #
(December 1993 MSS Calibration)

In Figure 3 HST pointing attitudes 1, 2, 3, and 10 occurred while HST was passing through the SAA region. Attitude pointings numbered 1, 3, and 10 showed Coarse Attitude angular deviations from the Fine Attitudes to be slightly greater than 0.6 degrees. The RSS deviation of the Coarse Attitudes versus the Fine Attitudes averaged 0.6 degrees over all of the HST pointings in the test sāmple of cases when the new MSS calibration parameters (December 1993) were used for input - Table 3 . In general the IGRF coefficients are supposed to be suitable for the magnetic field modeling in the SAA regions. Whether this becomes a problem or not in a future calibration attempt to slightly improve the accuracy of the MSS calibration parameters will have to be investigated further.

6.0 1990 INTERNATIONAL GEOMAGNETIC REFERENCE FIELD (IGRF) COEFFICIENTS AND UPDATES

In September of 1994 the MSS calibration software was updated to use a more current set of International Geomagnetic Reference Field (IGRF) coefficients - referenced to 1990. The previous IGRF coefficients available in the operational database were referenced to 1985. No information is currently available that quantifies what changes could be expected in the MSS calibration accuracies when changing over from the 1985 to the 1990 earth magnetic field model. All of the calibrations performed up to March 1994 used the 1985 IGRF coefficients. All of the accuracy requirements initially allocated for the HST Magnetic Sensing System sensors prior to HST launch were met following the HST First Servicing Mission MSS recalibration effort beginning in December 1993. A new MSS calibration may be undertaken in 1996 if 1995 IGRF coefficients become available then.

7.0 FUTURE ENHANCEMENTS

Redo MSS calibration with a 4 dipole model for the MTE based on the true locations of each torquer bar.

Redo the calibration as soon as the most current IGRF coefficients become available.

If the calibration is redone, it would be desirable to extend the data collection over one year to bridge gaps in HST pointings due to the sun's position on the celestial sphere.

Create a graphic utility to view the HST locations over the earth where the geomagnetic field is being sampled. Currently this done by hand calculation.

A method for acquiring MSS calibration data involves the use of the large scale maneuvers performed to calibrate the scale factor and alignment matrices of the HST Rate Gyro Assembly. FINATT is capable of computing attitudes during HST vehicle maneuvers. Beside the initial inaccuracies inherent in spacecraft attitude determination due to the uncalibrated Fixed Head Star Tracker (FHST) alignments the star position uncertainty would be affected by a star position signal lag of 75 milliseconds - Ref. 6, Section 3.3.6.4. For a typical spacecraft maneuver rate of 6 degrees per minute the star position signal lag would introduce an offset inaccuracy of 27 arcseconds. Special arrangements and bright object avoidance planning would have to be made with the HST Pointing and Control Systems Engineers for permission to leave on the Fixed Head Star trackers running in MAP mode during the maneuver. A typical 6 degrees per minute vehicle maneuver should present no problems for a FHST's ability to lock a moving object and perform the usual dwell measurement for 20 seconds while the sensor is in map mode. A copious amount of data is currently available that shows the FHSTs locking onto moving targets, for example satellites, while operating in mapping mode and showing position displacements of 2-3 degrees over the 20 second tracking dwell time, - Figure 5. Magnetic moments from the torquers increase dramatically just prior to vehicle maneuver. Such a quick calibration capability for MSS scale, alignment, bias, and torquer coupling would have been especially helpful during the orbital verification deployment of HST and immediately thereafter. The large amount of time available prior to the launch of HST may have allowed for the development of a strategy to collect FHST data and avoid bright light occultation zones.

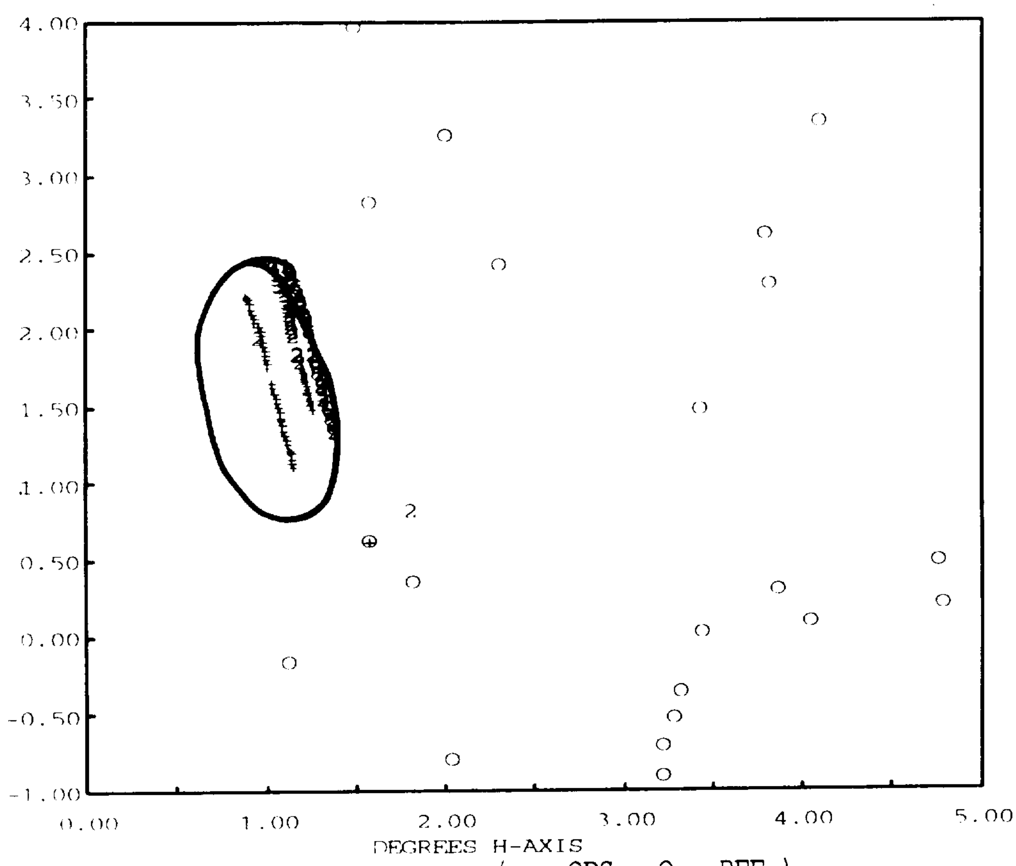


Figure 5: STS-61 observed in FHST-1 (1993.344 14:56:20 -14:57:30)

8.0 REFERENCES

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